Higgs at CLIC

Frank Simon
Max-Planck-Institut für Physik
Munich, Germany

on behalf of the CLIC Detector and Physics Study

Snowmass HEF Meeting, BNL

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Outline

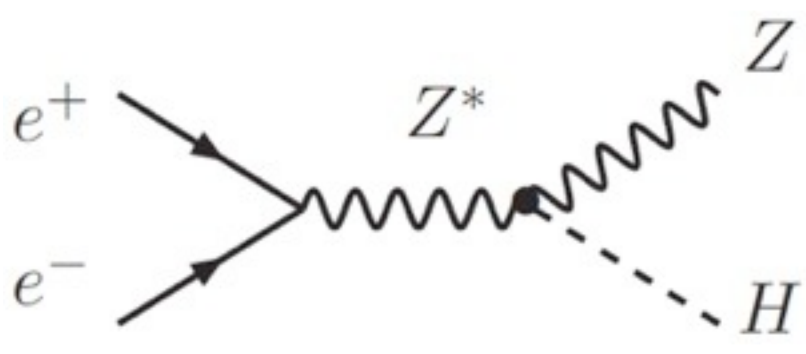
- Overview - Higgs Physics in e^+e^- collisions from 350 GeV to 3 TeV
- CLIC in Stages
- Making Measurement at CLIC
- The Staged Higgs Program
  - 375 GeV
  - 1.4 TeV
  - 3 TeV
- Summary

References

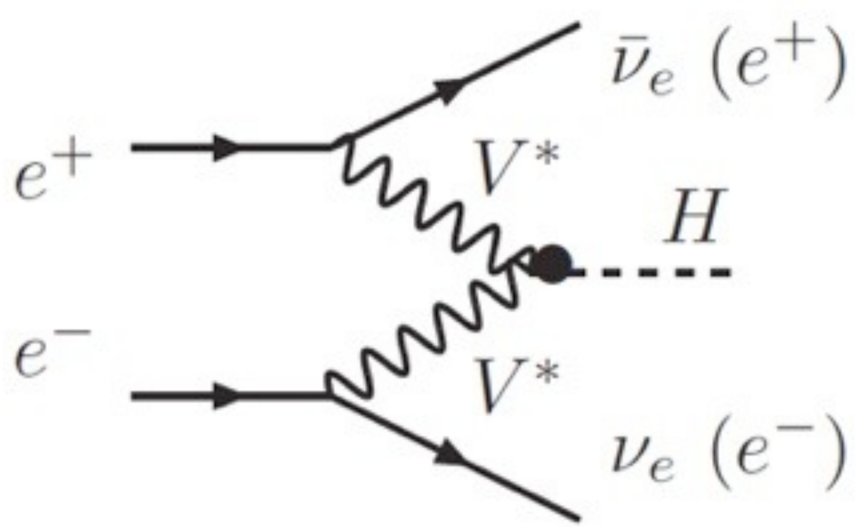
- Brau et al., The physics case for an e^+e^- linear collider, arXiv:1210.0202
- CLIC CDR (#1), A Multi-TeV Linear Collider based on CLIC Technology, https://edms.cern.ch/document/1234244/
- CLIC CDR (#2), Physics and Detectors at CLIC, arXiv:1202.5904
- CLIC CDR (#3), The CLIC Programme: towards a staged e^+e^- Linear Collider exploring the Terascale, arXiv:1209.2543

Overview - Higgs Production in e^+e^- Collisions

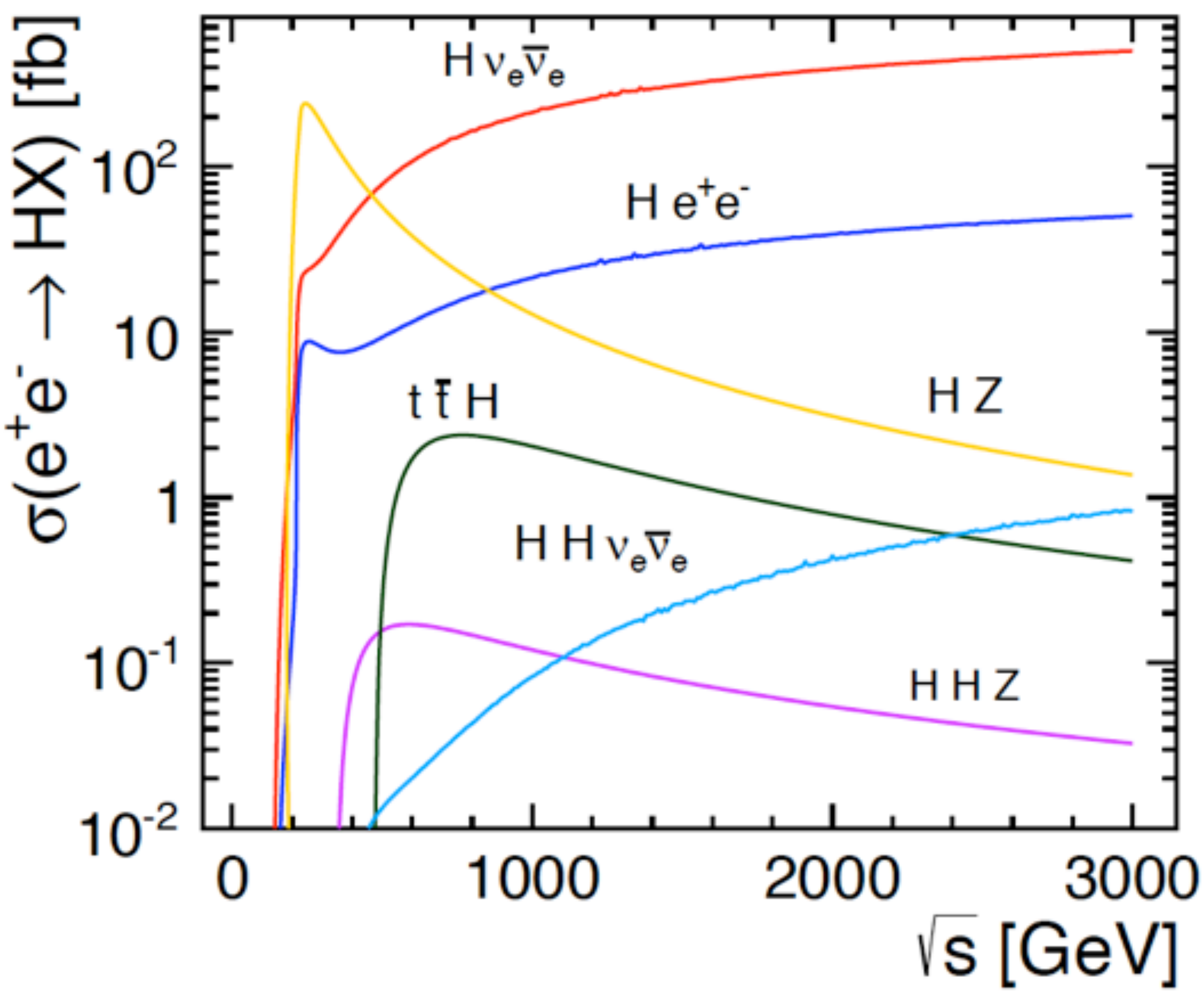
- The leading Higgs production modes in e^+e^- annihilation:



Higgs-Strahlung (s-channel process):
Dominates from threshold
up to ~ 400 GeV

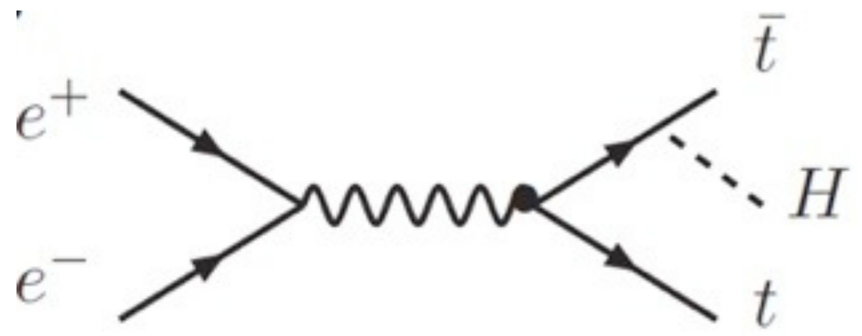


Vector boson fusion (t-channel process):
Dominates above ~ 500 GeV

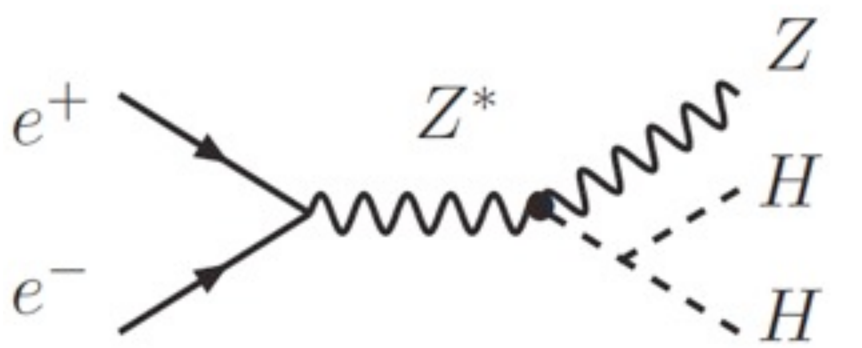


Overview - Higgs Production in e^+e^- Collisions

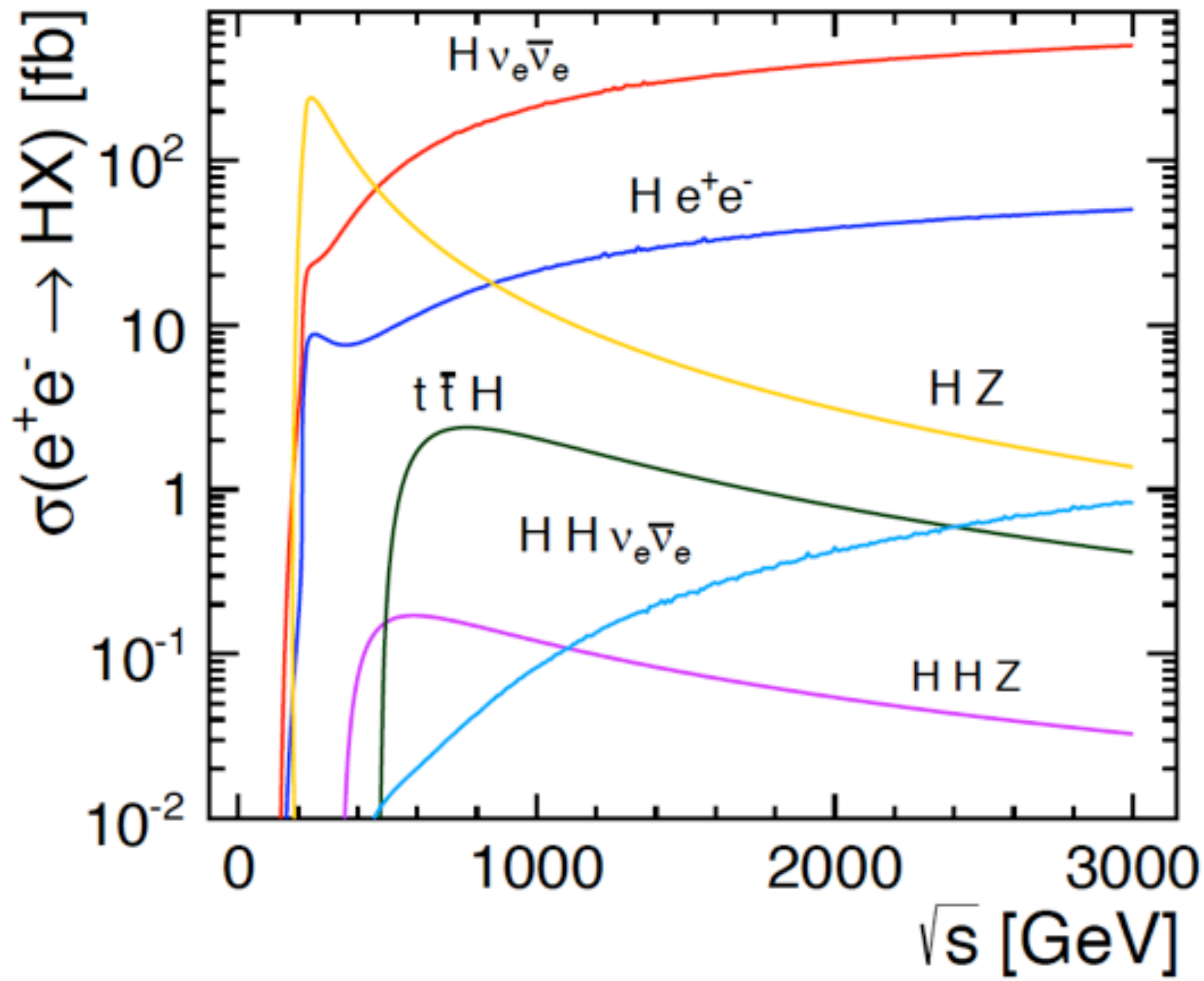
- Sub-leading processes - top Yukawa coupling, self-coupling

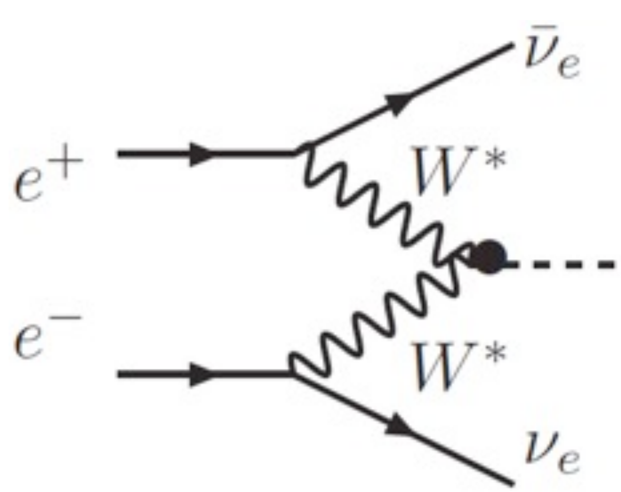


Higgs Strahlung off top quarks (s-channel)



Double Higgs production in
Higgs-Strahlung(s-channel)

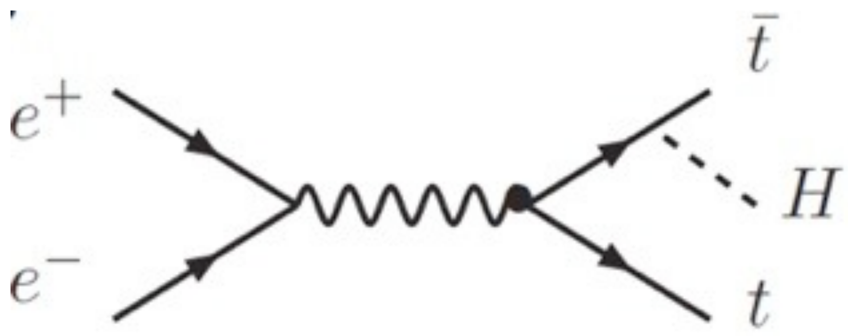




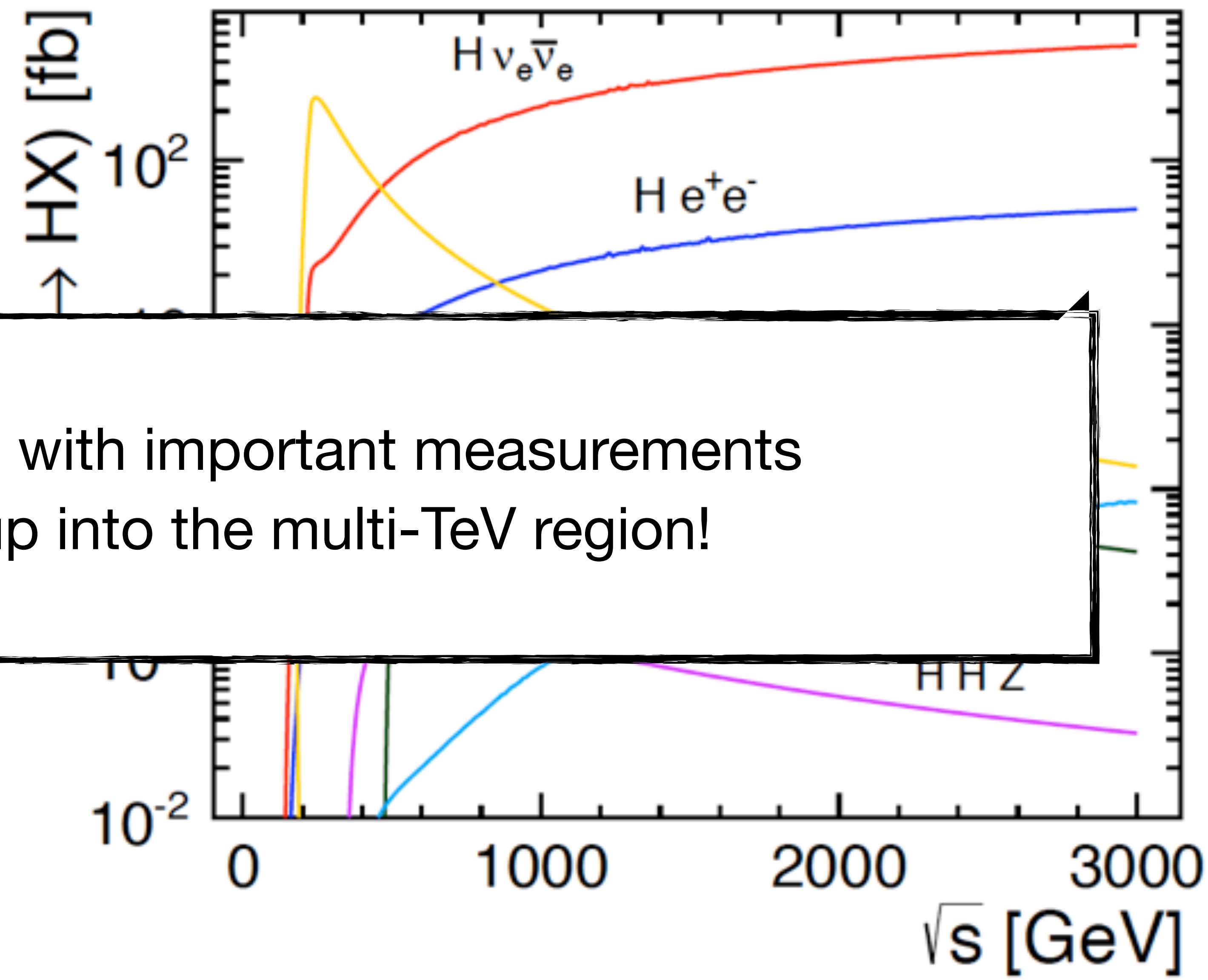
Double Higgs production in
vector boson fusion (t-channel)

Overview - Higgs Production in e^+e^- Collisions

- Sub-leading processes - top Yukawa coupling, self-coupling

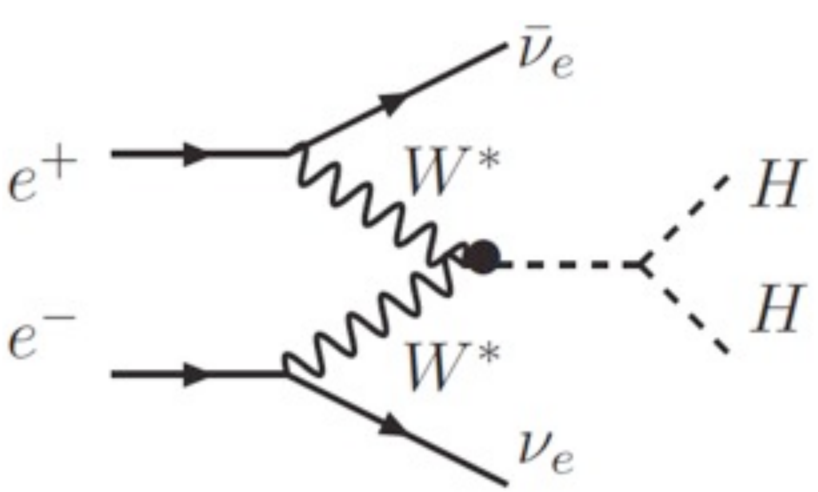


Higgs Strahlung off top quarks (s-channel)



A wide physics program - with important measurements from below 500 GeV up into the multi-TeV region!

Double Higgs production in Higgs-Strahlung(s-channel)

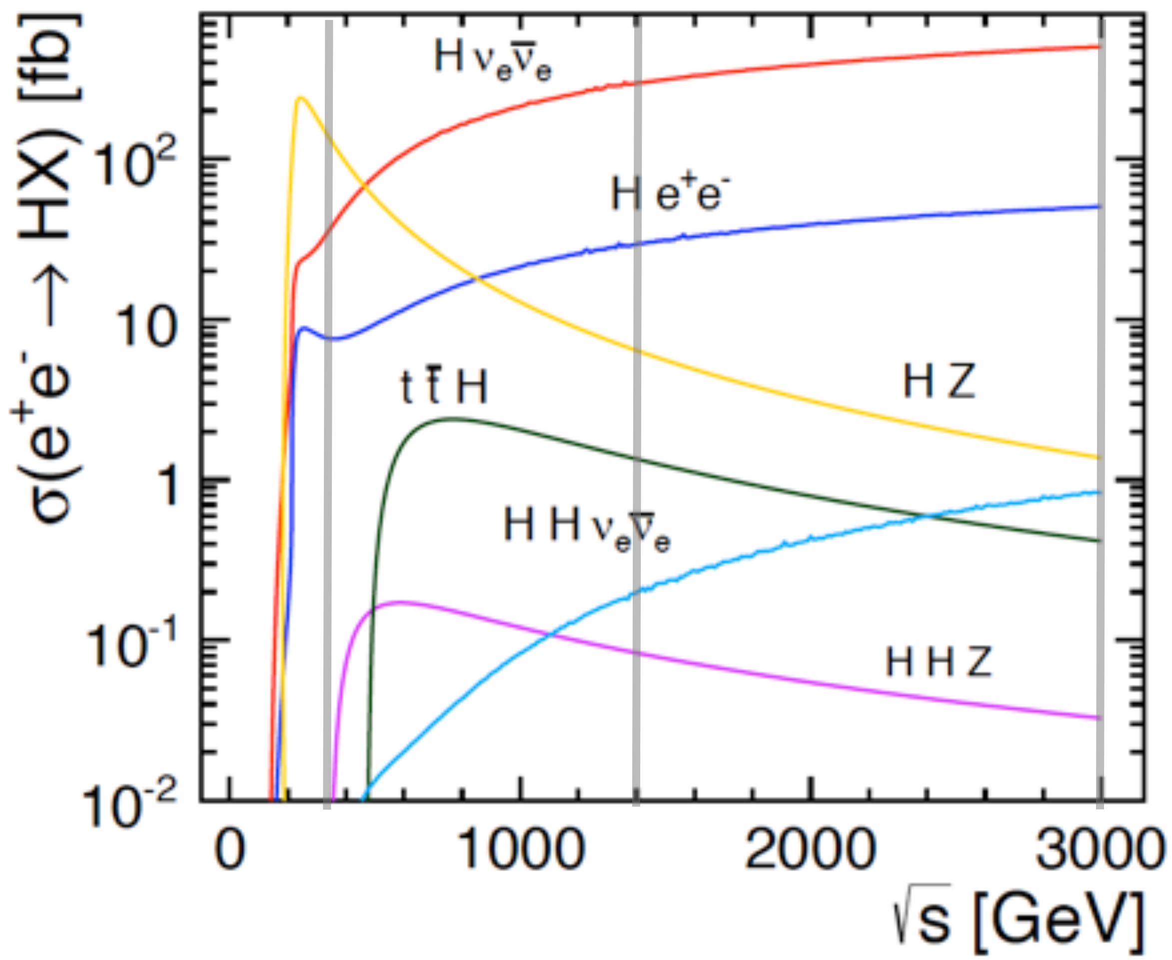


Double Higgs production in vector boson fusion (t-channel)

CLIC - A Staged Machine Exploring the Higgs

- CLIC will be implemented in stages: Optimized running conditions over a wide energy range
  - The best choice for the stages is defined by physics, with some additional technical considerations
    - May change with additional discoveries
- The current view: Three stages
  - 375 GeV, 500 fb^{-1}, includes top threshold
    Measure HZ coupling, various branching ratios, W/Z coupling ratio
  - 1.4 TeV, 1.5 ab^{-1}
    Measure ttH, self-coupling
  - 3 TeV, 2 ab^{-1}
    Highest energy to maximize physics reach, measure self-coupling, BRs with high precision

<u>primary goal:</u> Search for and measurement of BSM phenomena!



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    BRs with high precision

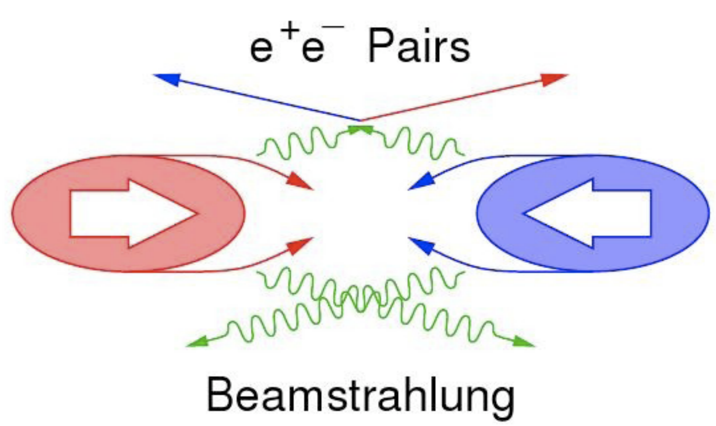
primary goal: Search for and measurement of BSM phenomena!

High statistics: a real Higgs factory!

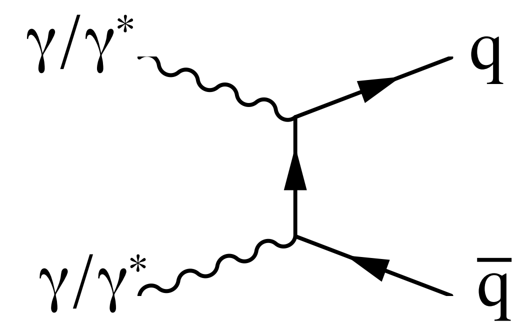
	No. of H (HZ & Hvv)
Stage 1 - 375 GeV	~ 80 k
Stage 2 - 1.4 TeV	~ 450 k
Stage 3 - 3 TeV	~ 1 M

Making Measurements at CLIC - Environment

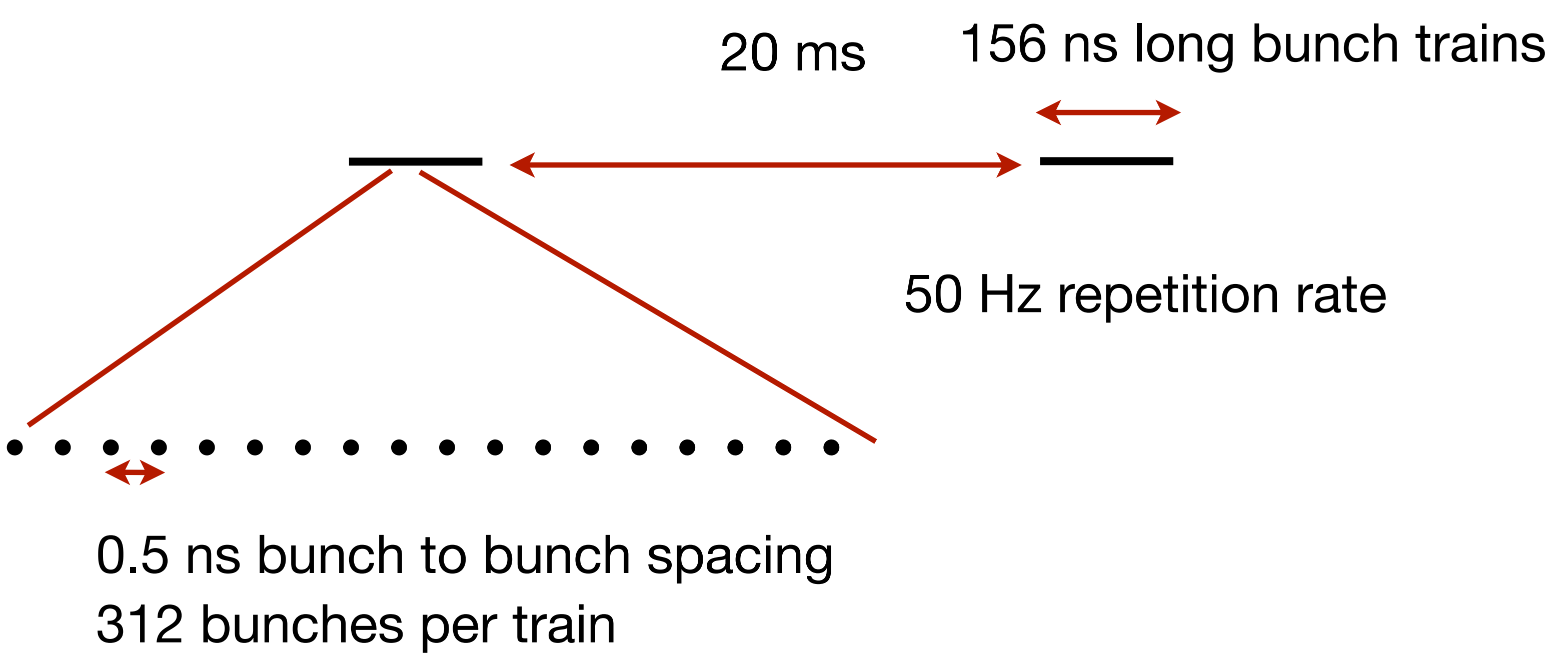
- The main challenge: High energy and high luminosity leads to high rates of photon-induced processes:



e^+e^- pairs drive crossing angle & vertex detector radius



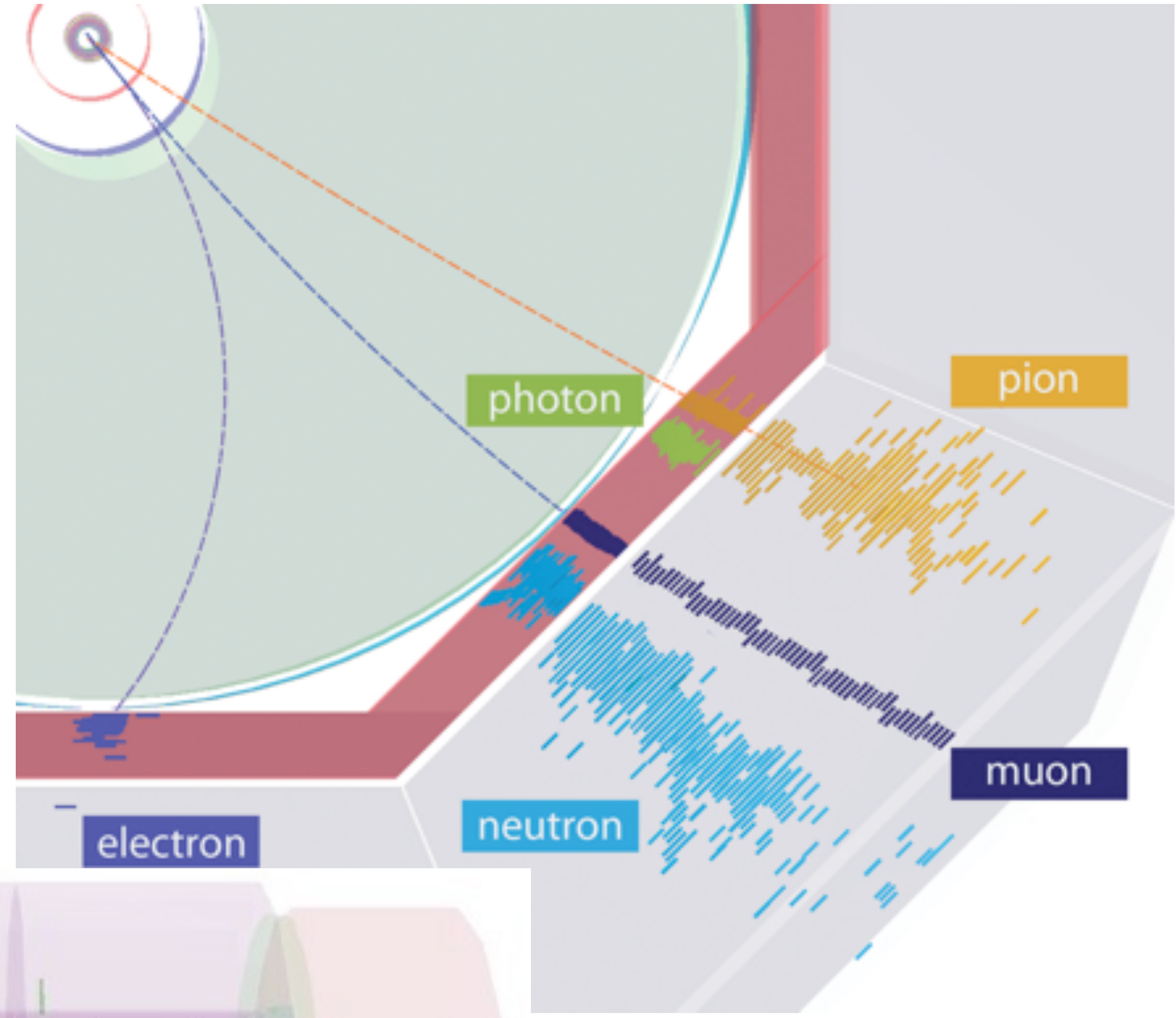
$\gamma\gamma \rightarrow$ hadrons interactions:
3.2 / bunch crossing @ 3 TeV

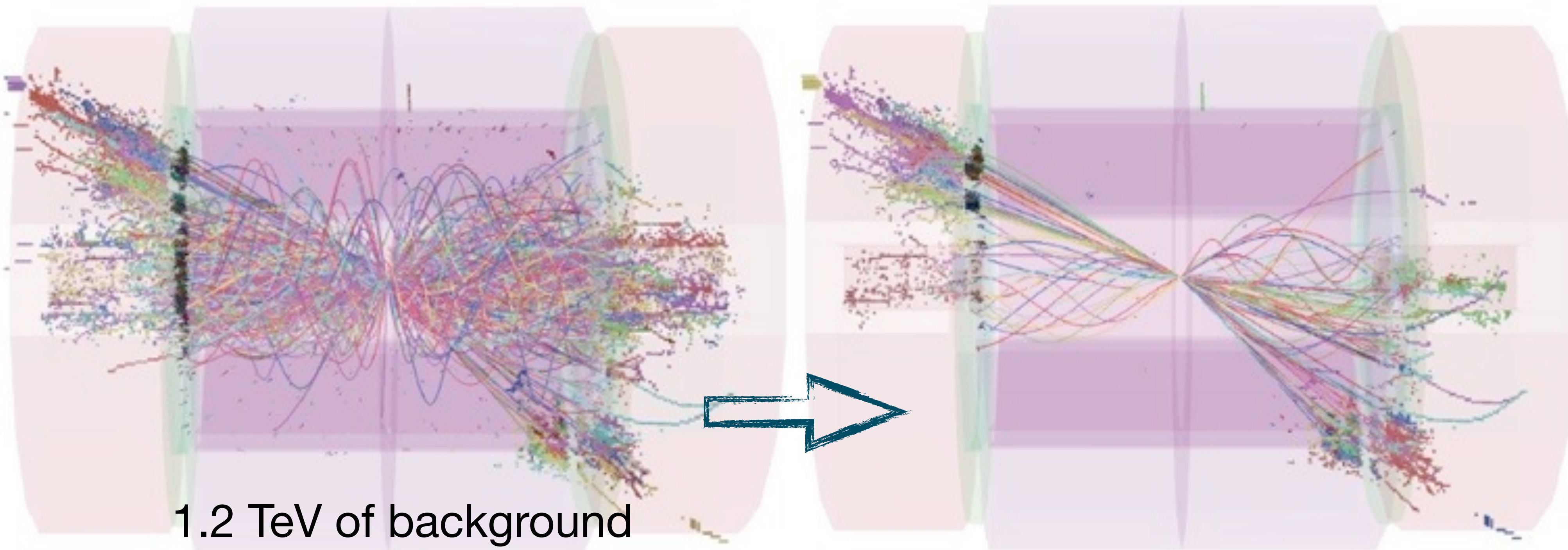


Combined with bunch structure:
Pile-up of hadronic background:
~ 19 TeV in HCAL / bunch train
⇨ Needs to be rejected by reconstruction

Making Measurements at CLIC - Reconstruction

- Event reconstruction based on Particle Flow Algorithms
  - Provides optimal jet energy reconstruction
  - When combined with ns-level timing in the calorimeters: A powerful tool for the rejection of γγ → hadrons background





$e^+e^- \to t\bar{t}$ @ 3 TeV

Reduction of background from 19 TeV to 100 GeV: Challenging CLIC environment under control!

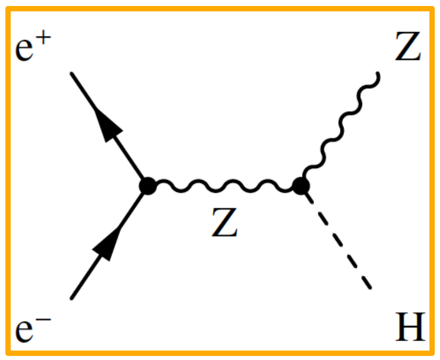
The Benchmark Studies

- Full simulation studies performed in the framework of the CLIC CDR
  - Realistic detector models
  - Full event reconstruction including PFA and timing and p_t based background mitigation
  - Inclusion of relevant physics backgrounds

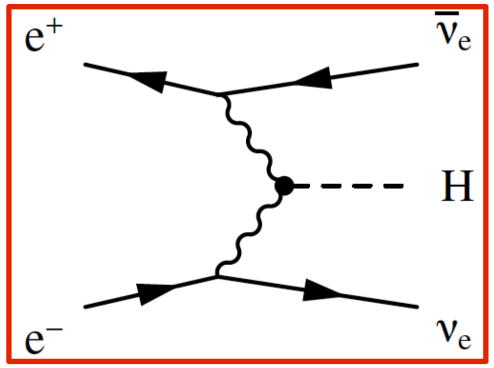
- Machine configurations in CDR studies:
  - 500 GeV (also operated at 350 GeV)
  - 1.4 TeV
  - 3 TeV

Higgs at Stage 1

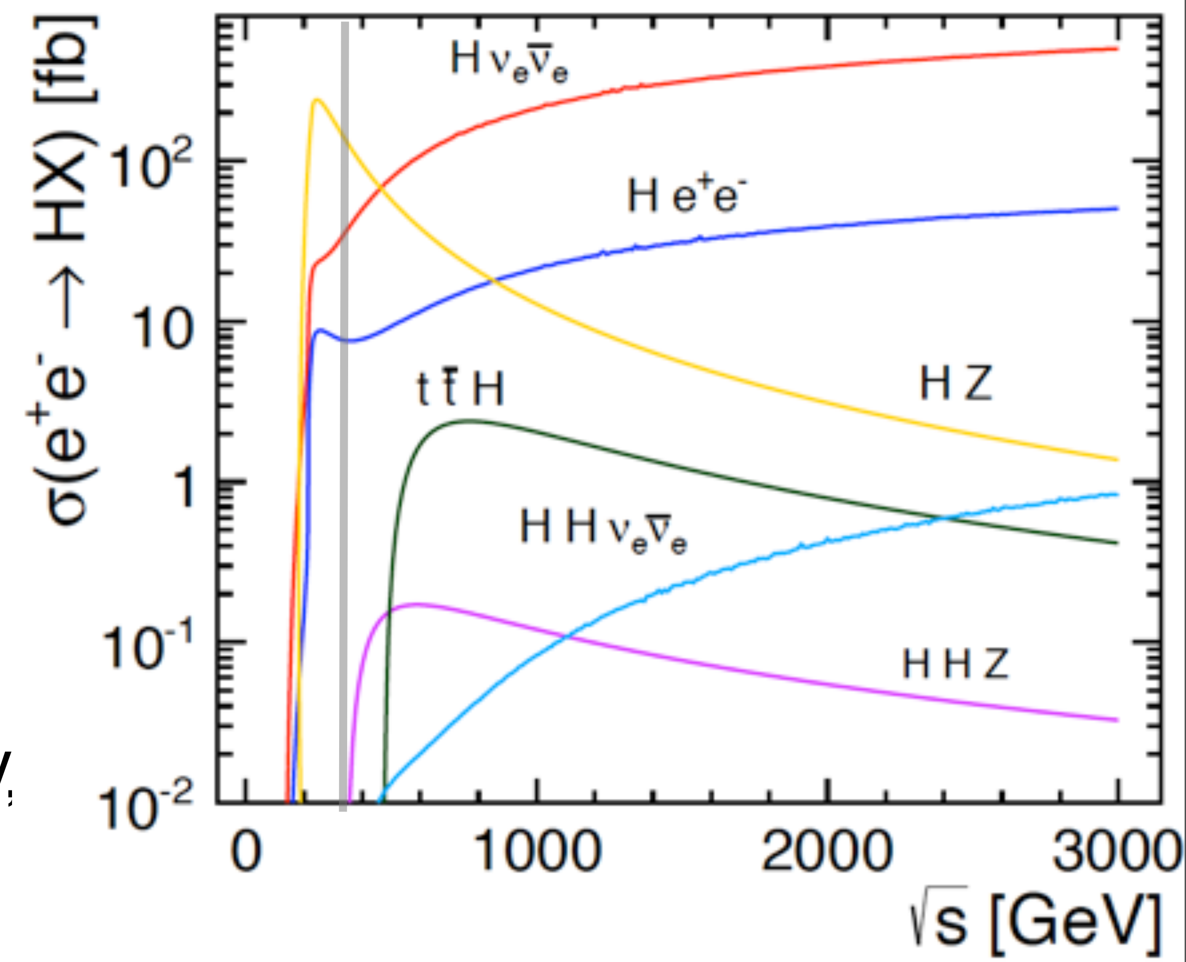
- At 350 GeV both Higgs-Strahlung and VBF contribute



~130 fb



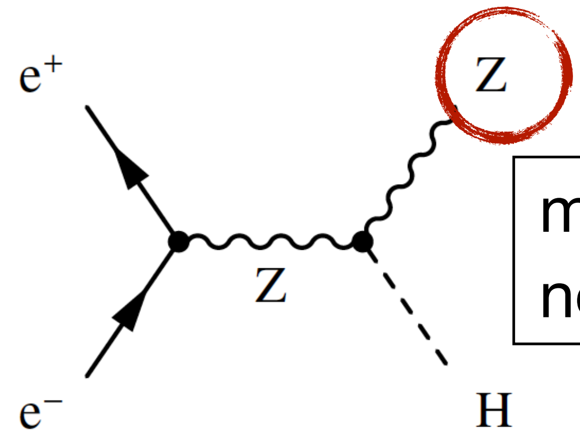
~30 fb



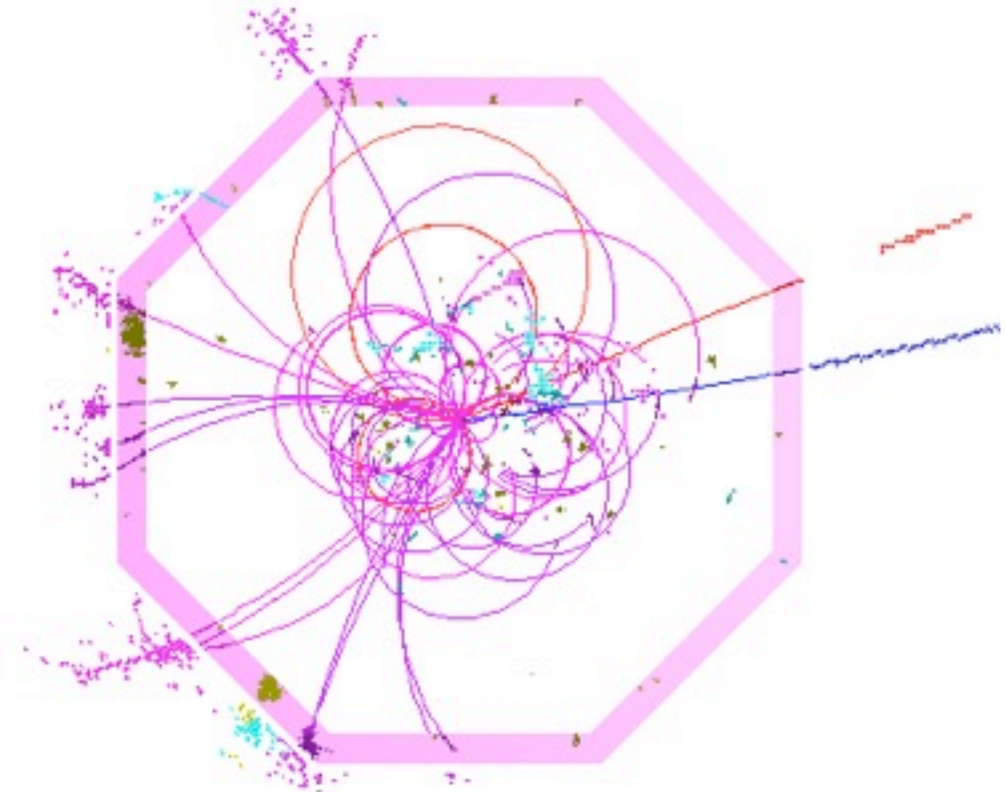
- Not the peak of the ZH cross section (~ 250 GeV, 240 fb), but higher instantaneous luminosity leads to comparable statistics for the same running time
  - Comparable precision on branching ratios
  - Slight penalty on recoil mass measurement - Large influence of muon momentum resolution

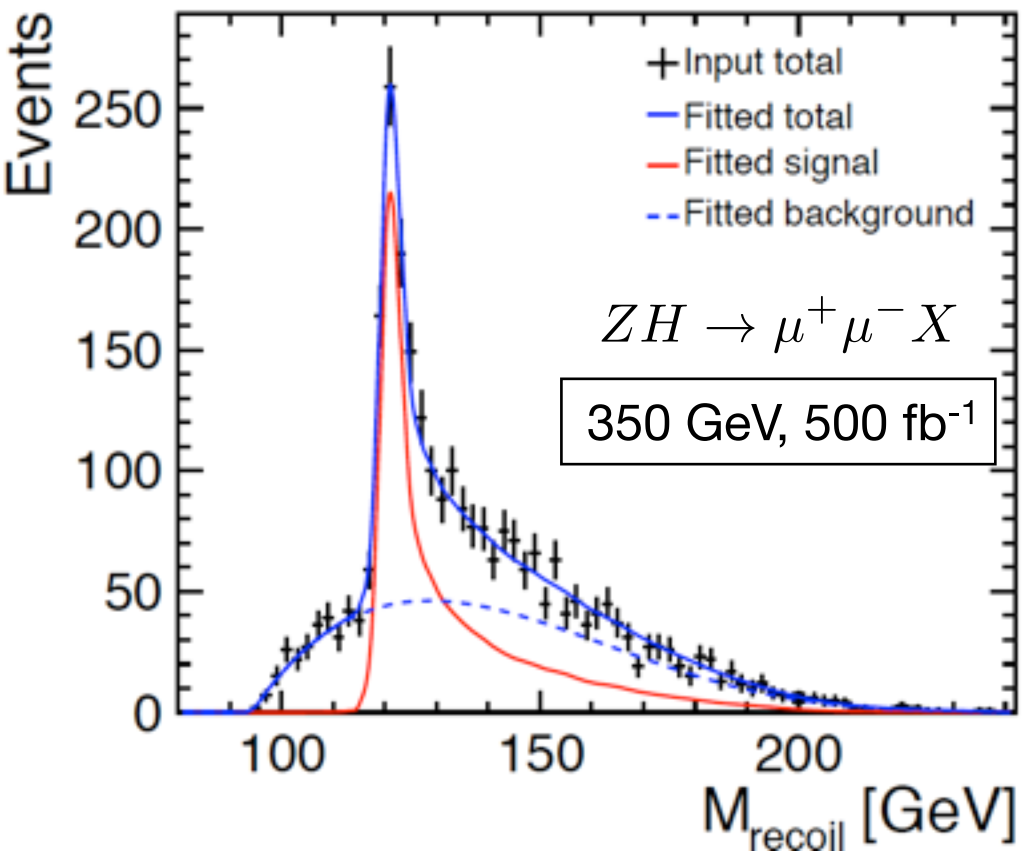
Higgs at Stage 1 - 350 / 500 GeV

- Model-independent coupling to Z



measure Z recoil
no assumptions on H decay





$$\frac{\Delta\sigma}{\sigma} = \sim 4\%$$

mass: Δm = ~ 120 MeV

mass: Δm = ~ 100 MeV
(with explicitly reconstructed final state at 500 GeV)

Higgs at Stage 1 - 350 / 500 GeV

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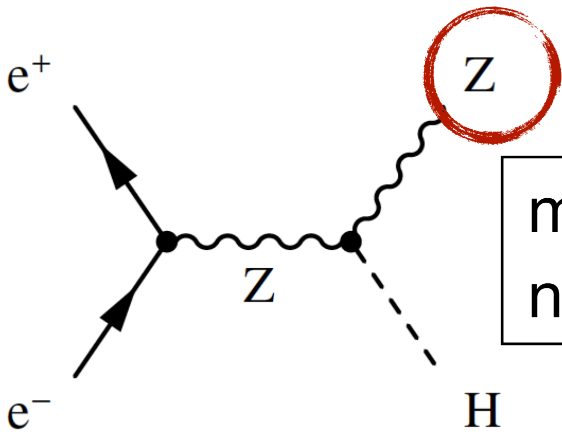

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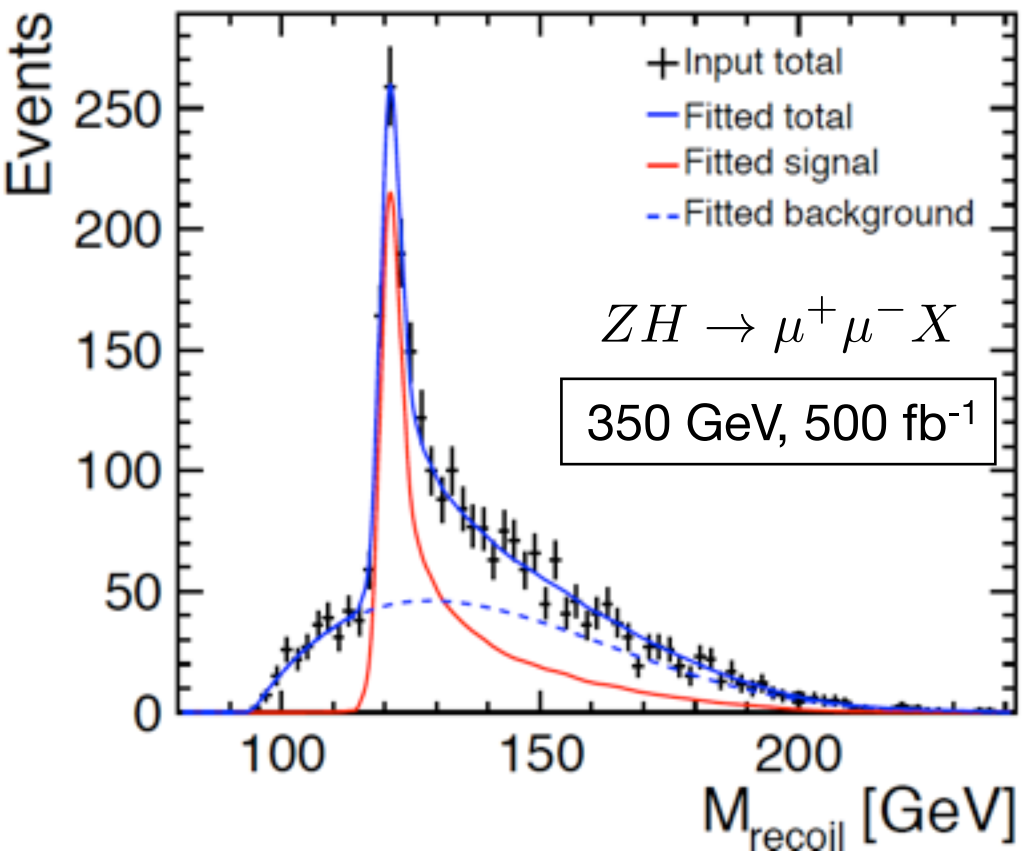

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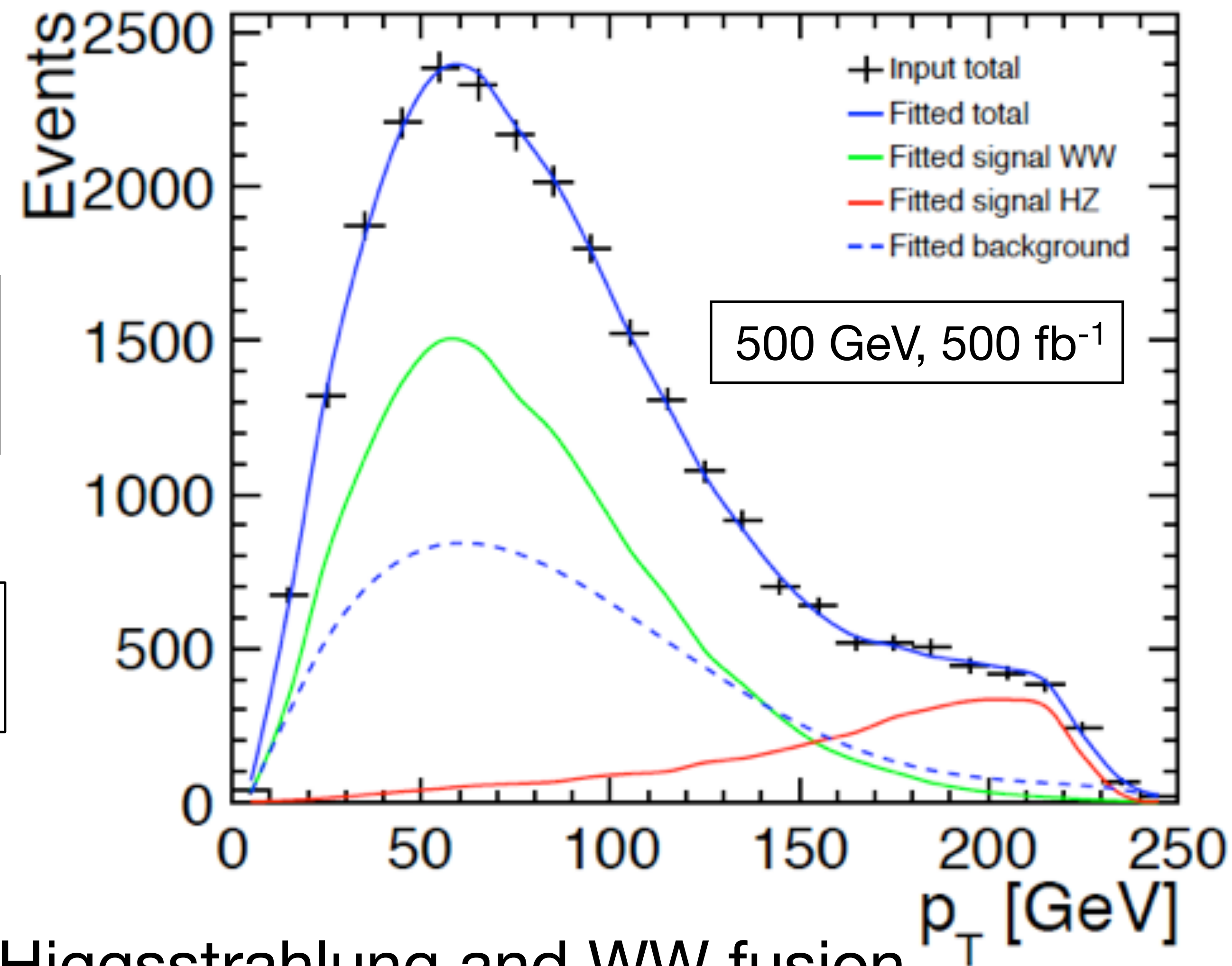
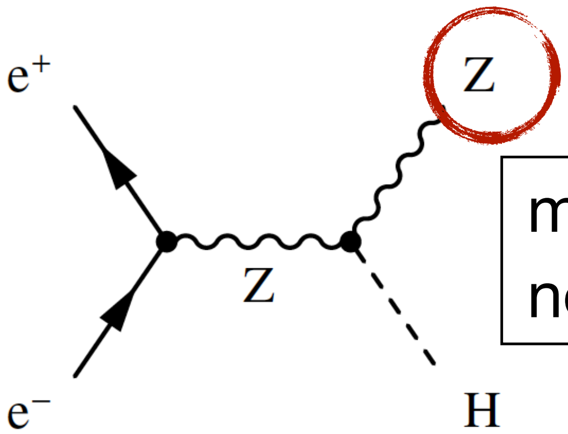


- Ratio of Higgsstrahlung and WW fusion provides access to coupling ratio - selection based on H p_T distribution

$$\Delta\frac{\sigma_{HZ}}{\sigma_{H\nu\nu}} =\sim 5\%$$

Higgs at Stage 1 - 350 / 500 GeV

- Model-independent coupling to Z



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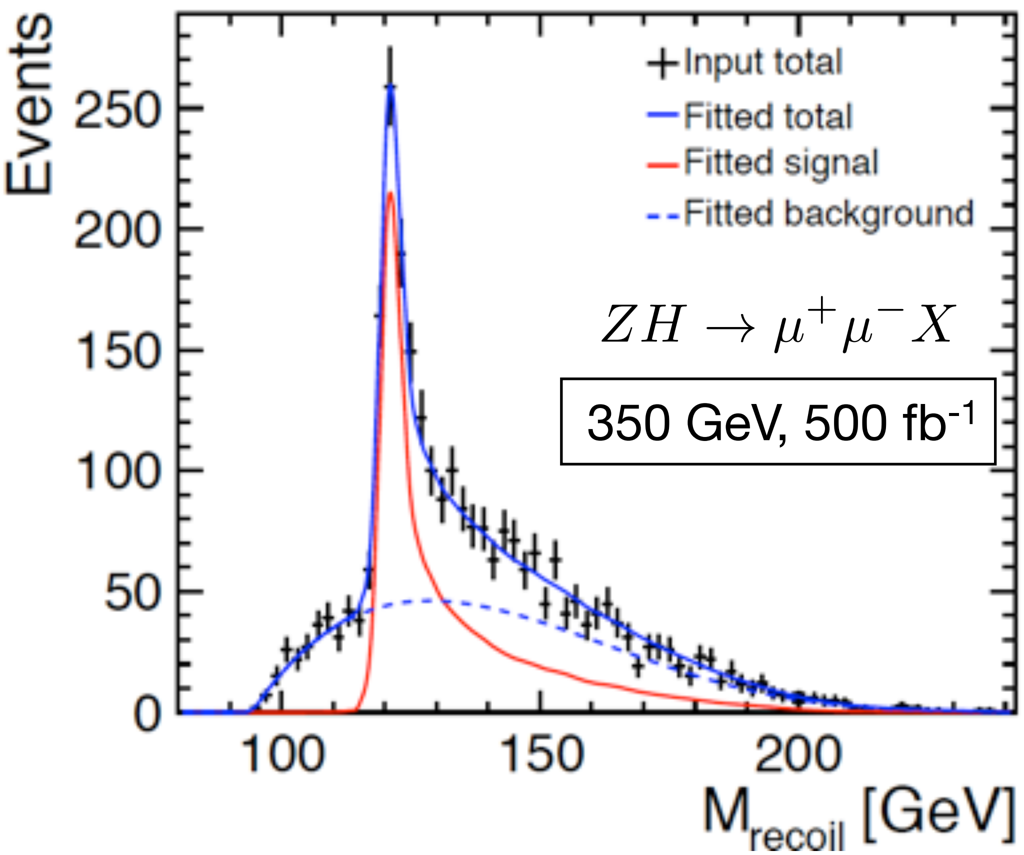

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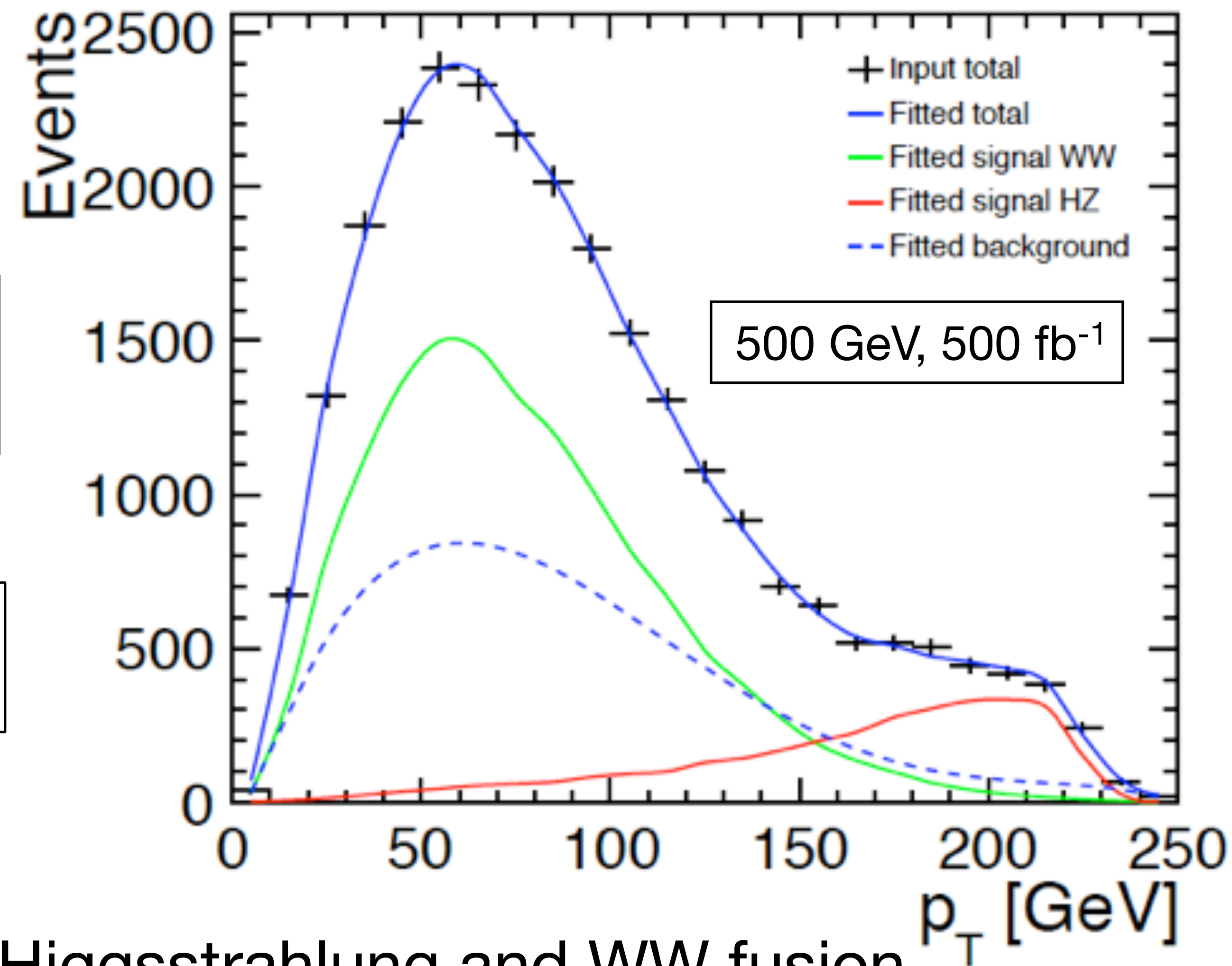


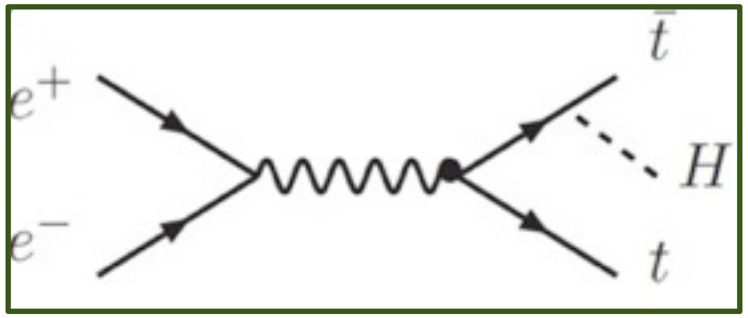
- Ratio of Higgsstrahlung and WW fusion provides access to coupling ratio - selection based on H p_T distribution

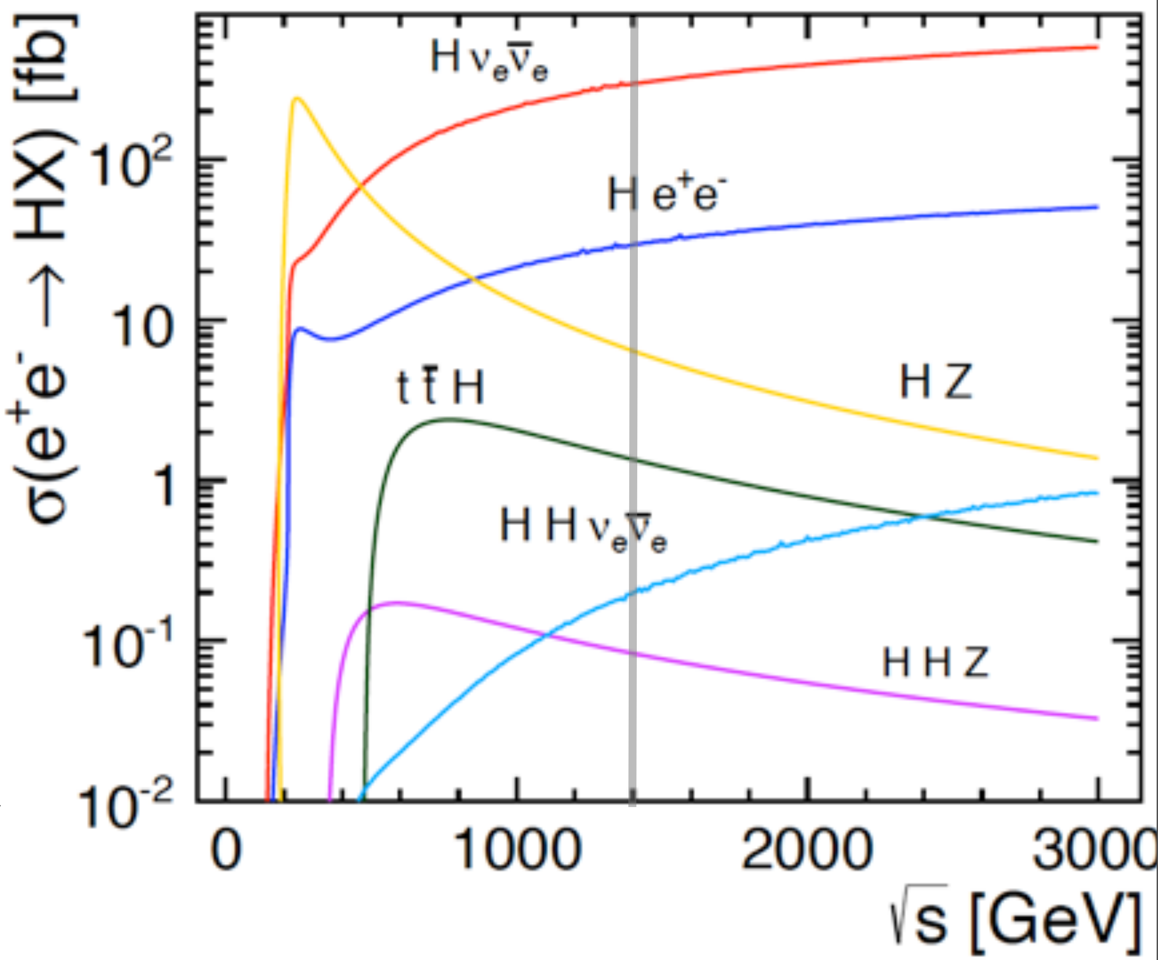
$$\Delta\frac{\sigma_{HZ}}{\sigma_{H\nu\nu}} =\sim 5\%$$

... and a several BR measurements: bb, cc, gg, ττ, WW*

Higgs at Stage 2 - 1.4 TeV

- Additional processes become available:
  - Higgs-top coupling





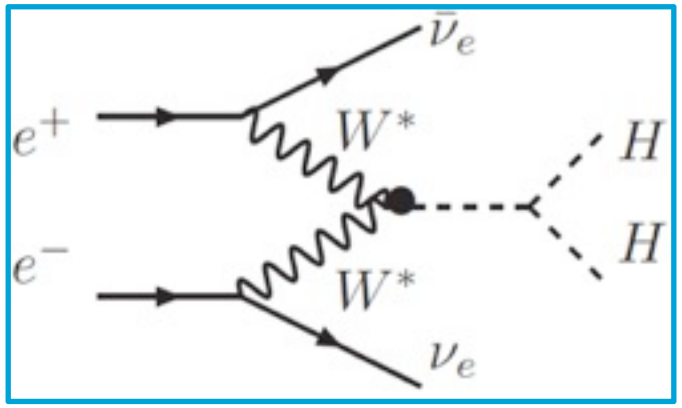
- Broad cross-section peak around 800 GeV
  - Backgrounds decrease with increasing energy
  - Take advantage of higher luminosity - Similar event counts at 1.4 TeV and 1 TeV, more favorable S/B

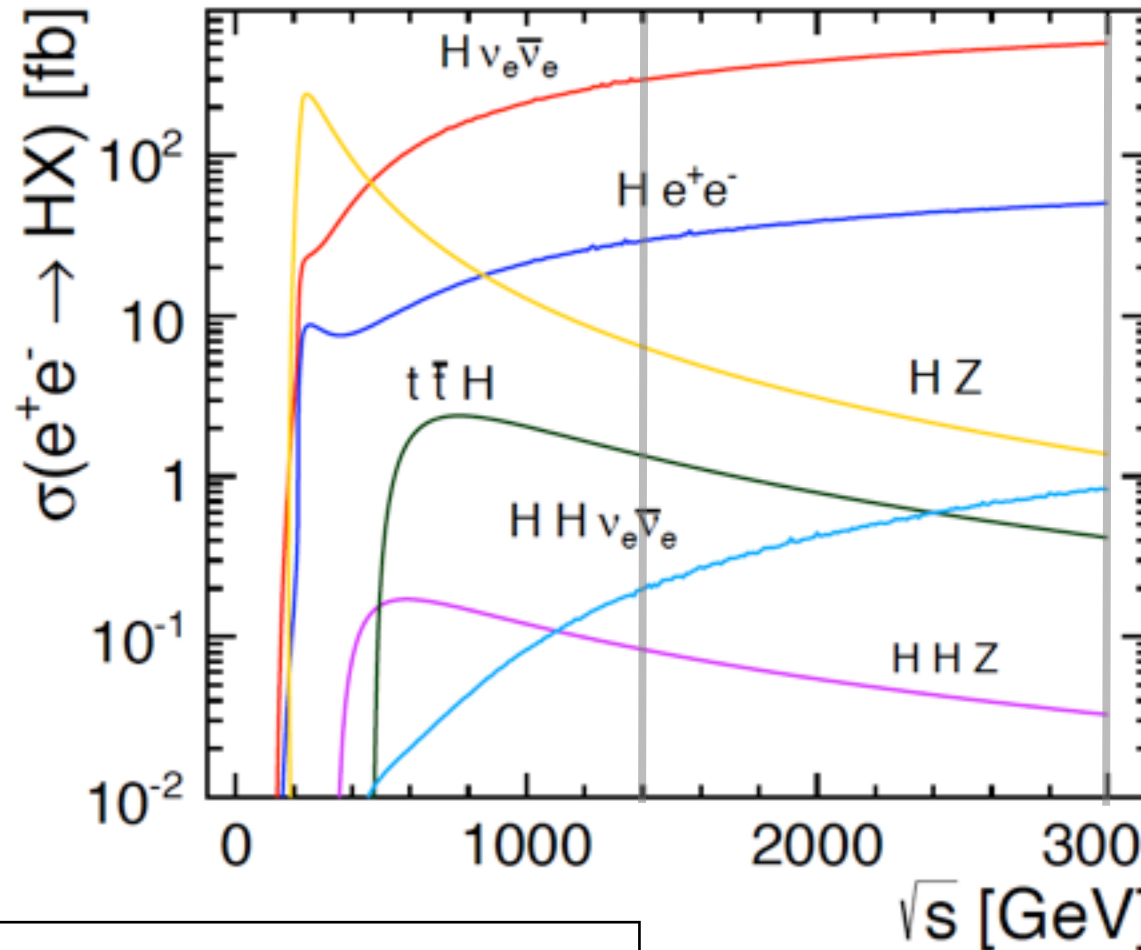
  - Full study in progress, expect $\boxed{\frac{\Delta\sigma}{\sigma} =\sim 8\%}$

  - Based on ILC 1 TeV study

Higgs at Stage 2 & 3 - 1.4 TeV & 3 TeV

- Additional processes become available:
  - Higgs self-coupling in WW fusion





- A challenging study: small cross section
  - 0.15 fb at 1.4 TeV, 0.6 fb at 3 TeV: a few 100 to 1000 events
    - Need high luminosity!
    - Need high energy! (t-channel process, increases with energy)

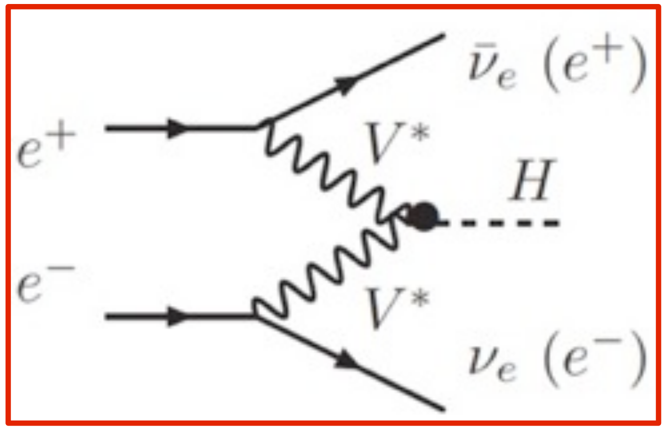
NB: 80% e^- polarization increases cross-section by 80%

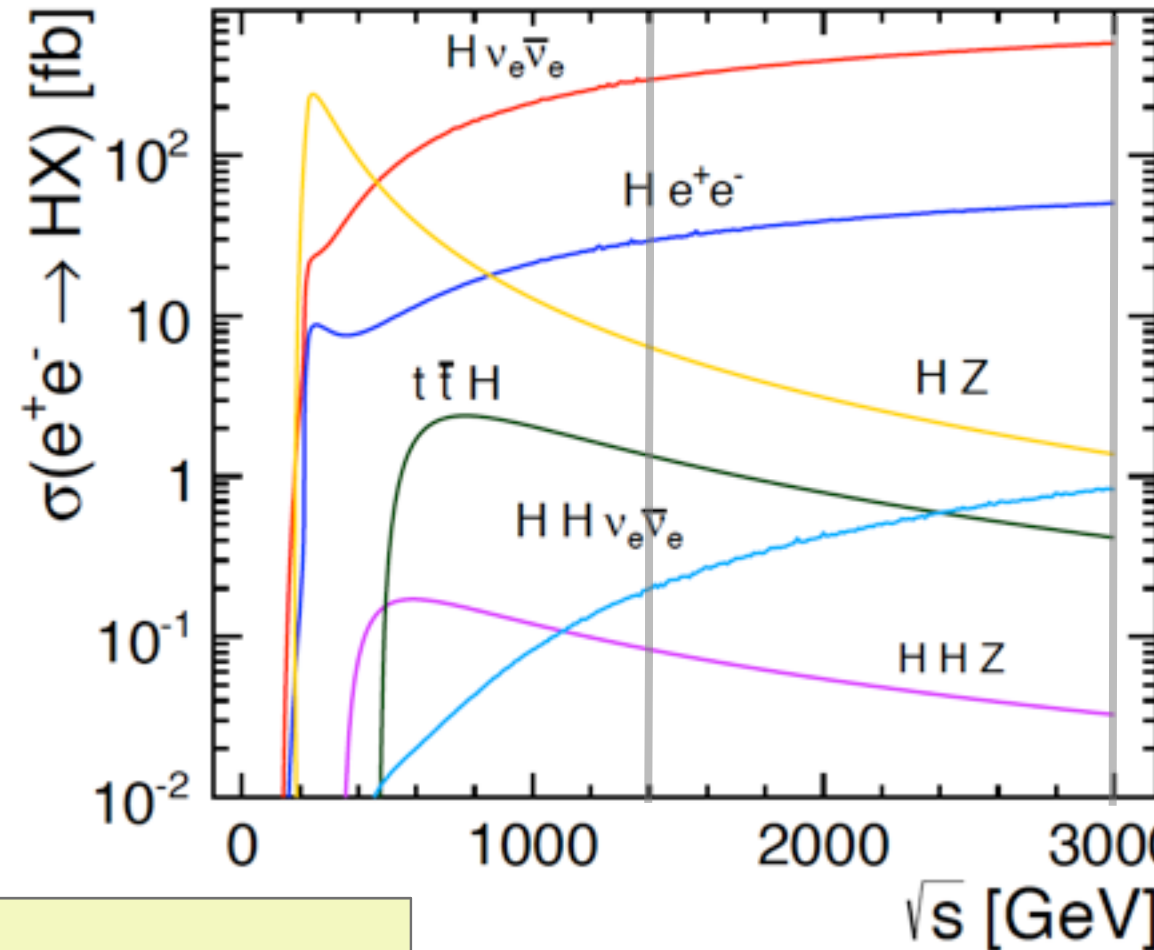
$\boxed{\dfrac{\Delta\lambda}{\lambda} \sim 30\%}$ 1.4 TeV, 1.5 ab^{-1} $\boxed{\dfrac{\Delta\lambda}{\lambda} \sim 16\%}$ 3 TeV, 2 ab^{-1} unpolarized

potential to improve to ~20% (1.4 TeV) and ~10% (3 TeV) with polarized electrons and further analysis improvement

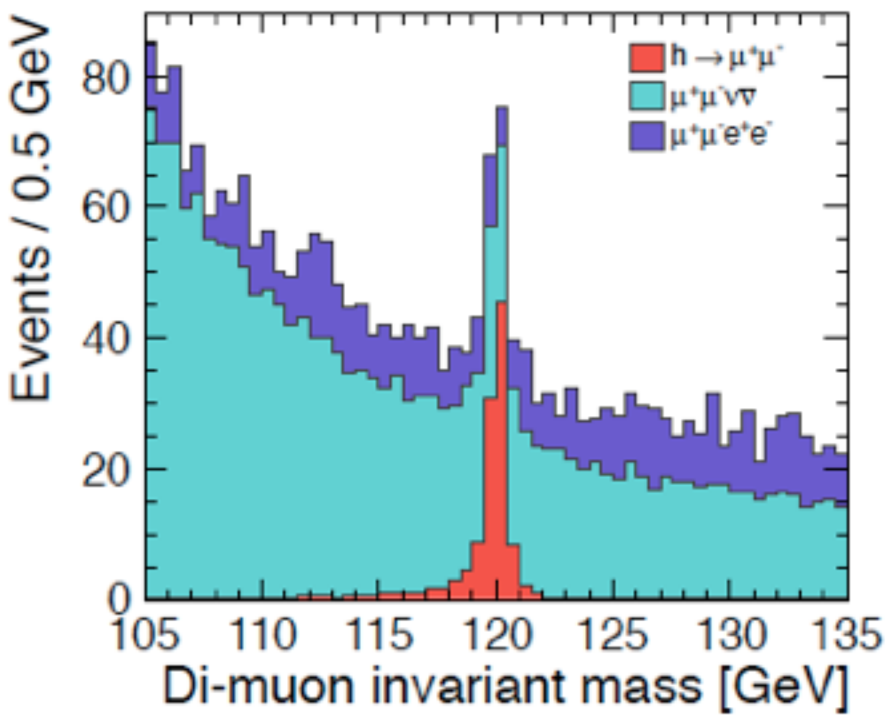
Higgs at Stage 2 & 3 - 1.4 TeV & 3 TeV

- Take advantage of high luminosity and increasing cross-sections in VBF





  - Precise measurement of large BR's, access to rare Higgs decays



$$\Delta(\sigma \times \mathrm{BR}(\mathrm{H} \to \mu^+\mu^-)) \sim 15\%$$

$$\Delta(\sigma \times \mathrm{BR}(\mathrm{H} \to \mathrm{b\bar{b}})) \sim 0.2\%$$

$$\Delta(\sigma \times \mathrm{BR}(\mathrm{H} \to \mathrm{c\bar{c}})) \sim 3.2\%$$

3 TeV

$$\Delta(\sigma \times \mathrm{BR}(\mathrm{H} \to \tau^+\tau^-)) < 3.7\%$$

1.4 TeV

A Study of the Full Higgs Program at CLIC

- 350 GeV
  - σ of **HZ** - model-independent HZZ coupling
  - σ x BR of **bb, cc, gg, WW*, ττ**
  - combined extraction of hadronic BRs
  - **Mass** and **σ(HZ)/σ(Hνν)** at 500 GeV
- 1.4 TeV
  - σ x BR of **bb, cc, gg, WW*, μμ, γγ, Zγ, ττ**
  - **ZZ fusion** - ratio of HZZ and and HWW couplings
  - combined fit of hadronic BRs, absolute coupling to W
  - σ of **ttH**
  - **self-coupling** (expecting improvement from further studies)
- 3 TeV
  - σ x BR of **bb, cc, μμ**
  - **self-coupling** (expecting improvement from further studies)
  - potentially also **ZZ fusion**

already done

completion expected by summer, including a combined fit of couplings

Higgs @ CLIC - Benchmark Results Summary

	Observable	stat. uncertainty	
HZ	σ	4%	350 GeV
HZ	mass	120 MeV	350 GeV
H → ττ	σ x BR	6.2%	350 GeV
HZ / Hνν	σ/σ	5%	500 GeV
HZ, H → bb	mass	100 MeV	500 GeV
H → ττ	σ x BR	< 3.7%	1.4 TeV; obtained with cut-reduced signal sample
HHνν	self-coupling λ	30%	1.4 TeV
ttH	σ	8%	1.4 TeV; estimated based on 1 TeV ILC study
H → bb	σ x BR	0.2%	3 TeV
H → cc	σ x BR	3.2%	3 TeV
H → μμ	σ x BR	15%	3 TeV
HHνν	self-coupling λ	16%	3 TeV

all based on full simulation studies with SM & beam-induced backgrounds
assuming unpolarized beams
(80% e^- polarization increases Hνν / HHνν cross-sections by ~ 80%)

The CLIC Detector & Physics Study

- Pre-collaboration structure based on a light-weight "Memorandum of Cooperation": http://lcd.web.cern.ch/LCD/Home/MoC.html

Australia: ACAS; Belarus: NC PHEP Minsk; Czech Republic: Academy of Sciences Prague; Denmark: Aarhus Univ.; Germany: MPI Munich; Israel: Tel Aviv Univ.; Norway: Bergen Univ.; Poland: Cracow AGH + Cracow Niewodniczanski Inst.; Romania: Inst. of Space Science; Serbia: Vinca Inst. Belgrade; Spain: Spanish LC network; UK: Birmingham Univ. + Cambridge Univ. + Oxford Univ.; USA: Argonne lab; + CERN

Additional members welcome!

Summary & Outlook

- CLIC is an exciting and realistic option for a future machine at the energy frontier
  - A wide physics program: Higgs, top, precision measurements, BSM up into multi-TeV region for strong and weak sector

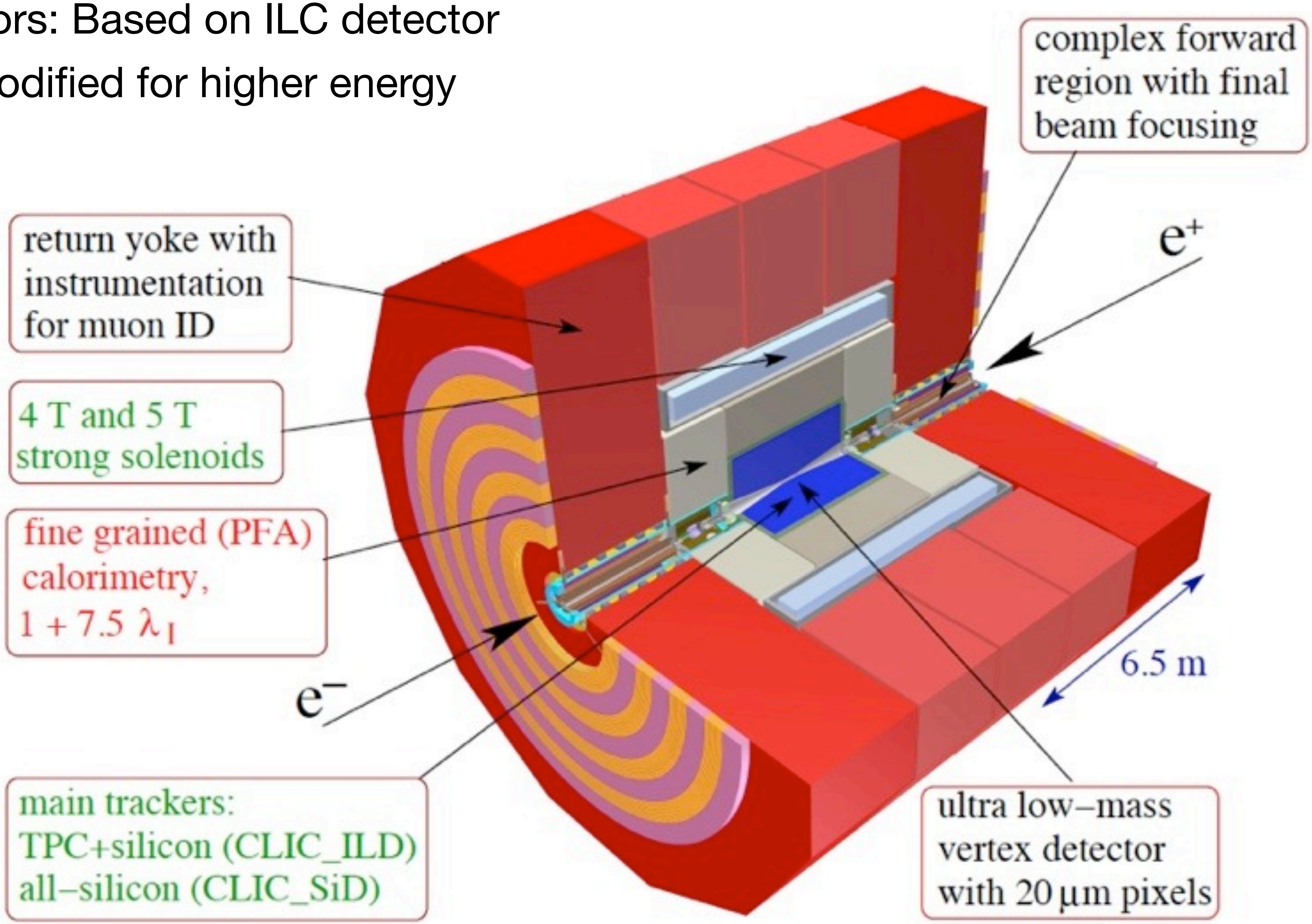
- A full exploration of the Higgs sector with precision measurements
  - Couplings to vector bosons - model-independent ZH coupling
  - Couplings to fermions, including rare decays and coupling to top
  - Higgs self-coupling

- Many results from full-simulation studies already available, with a comprehensive study on the way, to be completed in summer

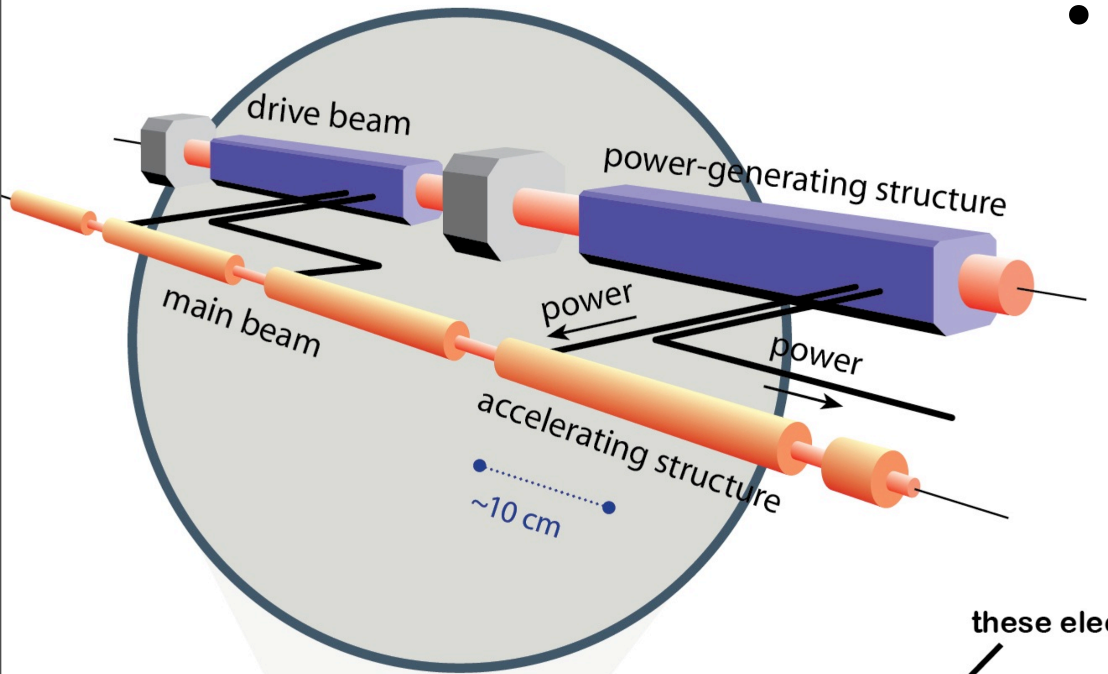
Backup

Making Measurements at CLIC - Detectors

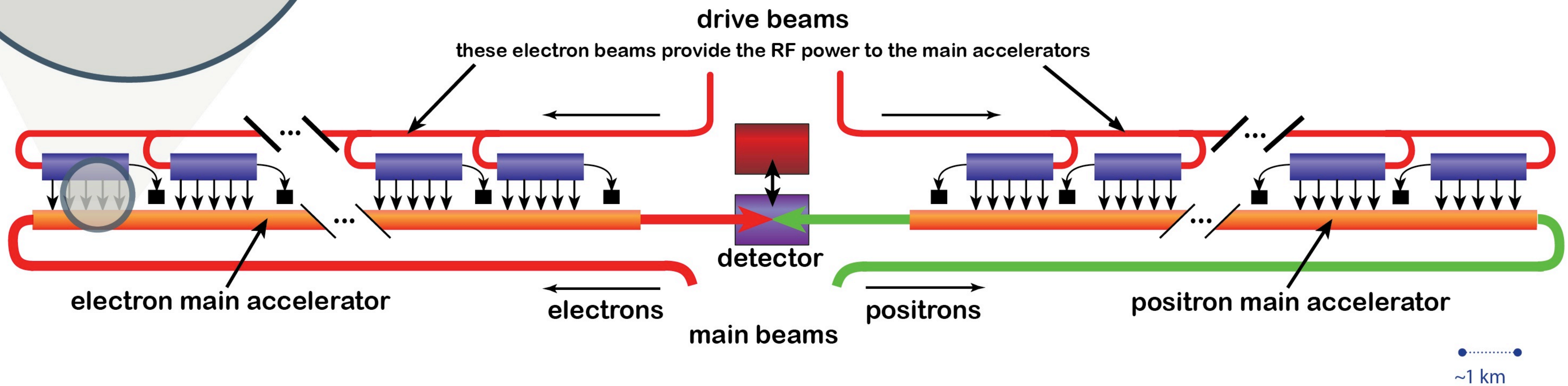
- CLIC detectors: Based on ILC detector concepts, modified for higher energy



CLIC - The Accelerator



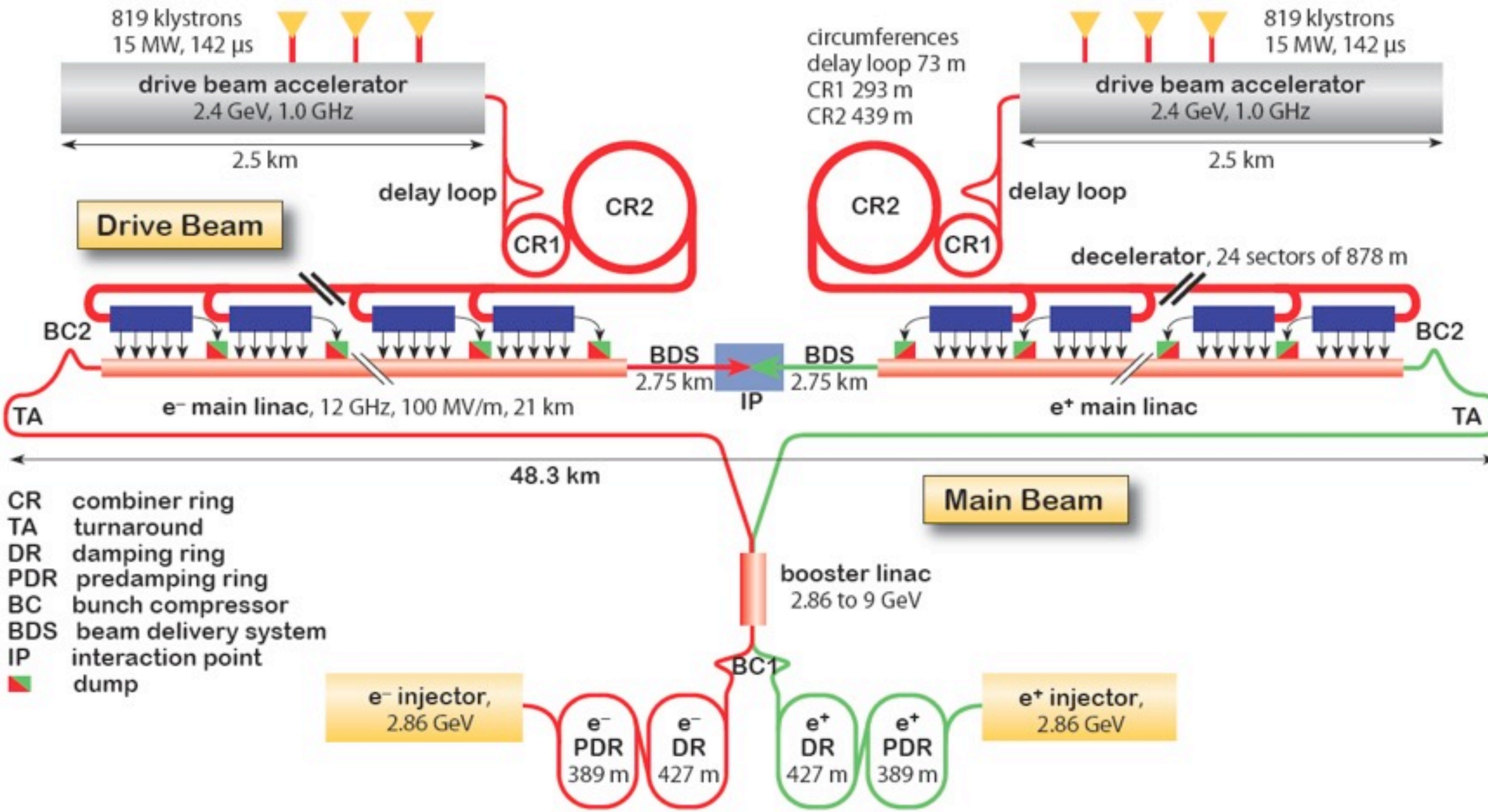
- Two-beam acceleration:
  - low-energy high current drive beam (2.4 GeV, 100 A)
  - high-energy main beam (1.2 A, 9 GeV - 1.5 TeV)
  - Acceleration gradient 100 MV/m
  - 12 GHz normal conducting RF cavities



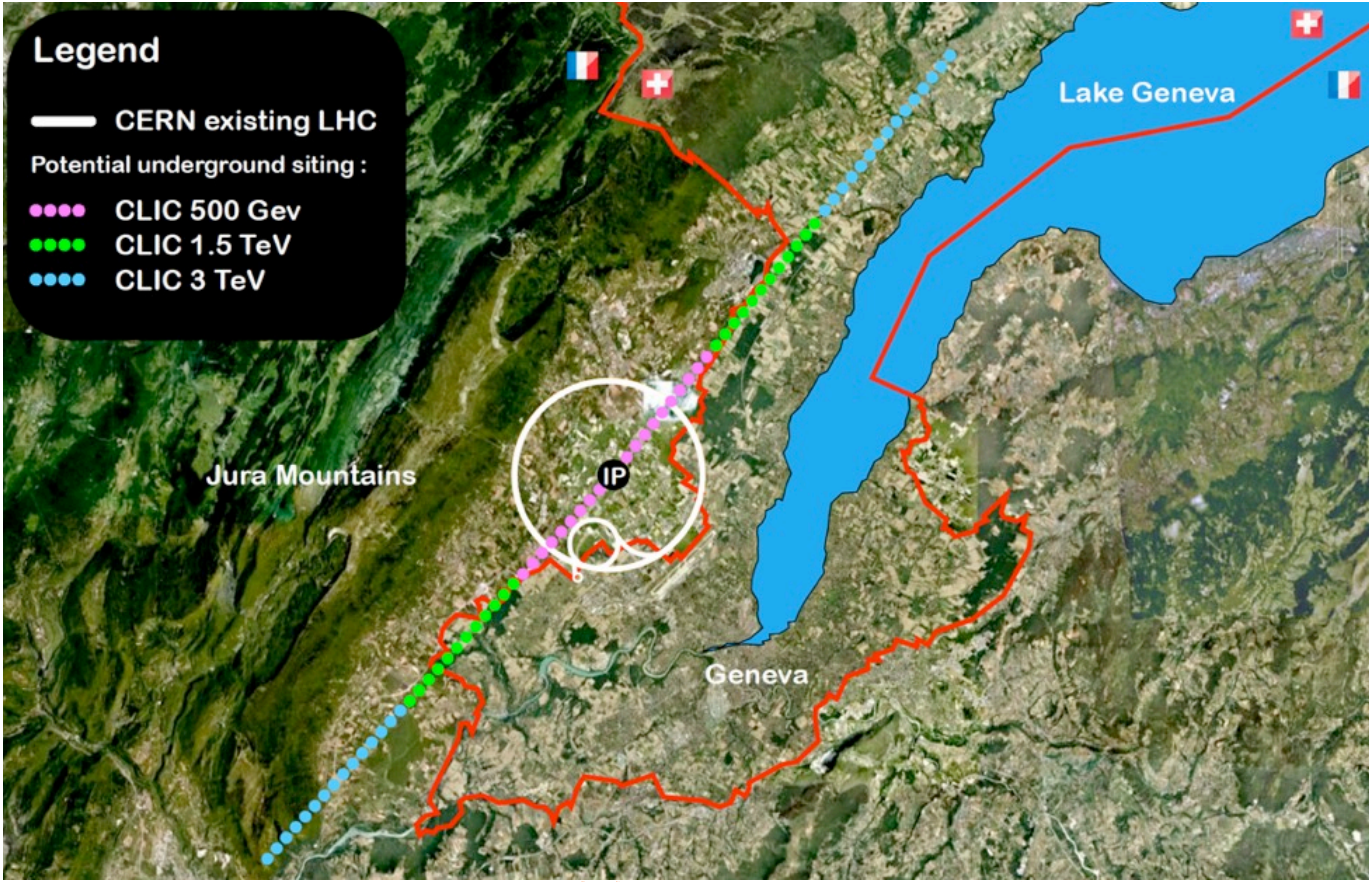
Three stages - CDR parameters

- 500 GeV - L 2.3 x 10^{34} $cm^{-2}s^{-1}$ ($L_{0.01}$ 1.4 x 10^{34} $cm^{-2}s^{-1}$)
- 1.4 TeV - L 3.2 x 10^{34} $cm^{-2}s^{-1}$ ($L_{0.01}$ 1.3 x 10^{34} $cm^{-2}s^{-1}$)
- 3 TeV - L 5.9 x 10^{34} $cm^{-2}s^{-1}$ ($L_{0.01}$ 2.0 x 10^{34} $cm^{-2}s^{-1}$)

CLIC - 3 TeV Layout



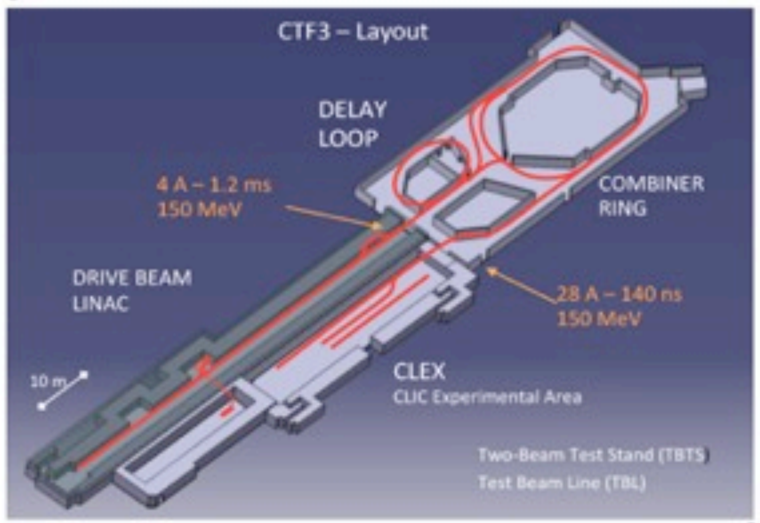
CLIC - Possible Implementation at CERN



CLIC - Towards Realization

2012-16 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.



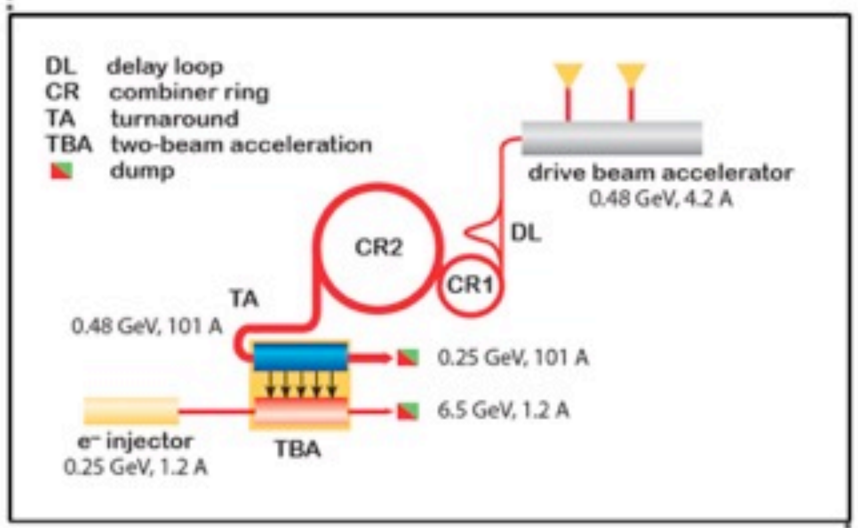
2016-17 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

2017-22 Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

Prepare detailed Technical Proposals for the detector-systems.



2022-23 Construction Start

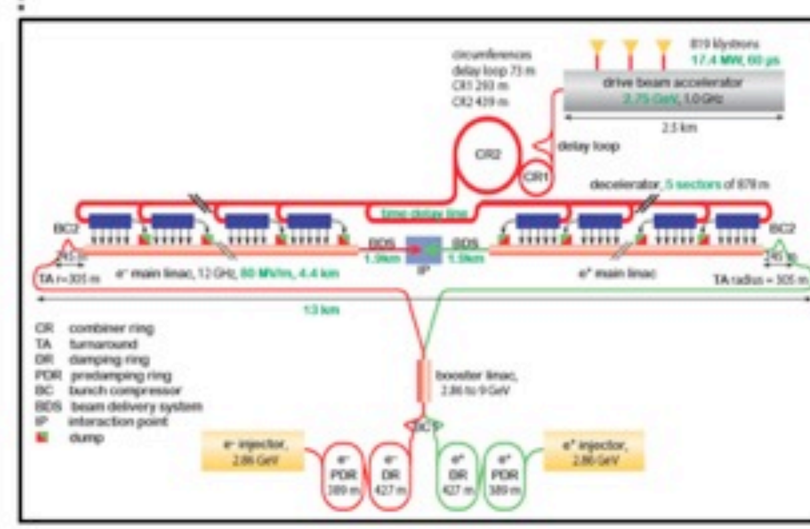
Ready for full construction and main tunnel excavation.

Faster implementation possible, for example with a klystron-based first stage as Higgs factory

2023-2030 Construction Phase

Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction.

Preparation for implementation of further stages.



2030 Commissioning

From 2030, becoming ready for data-taking as the LHC programme reaches completion.